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R.D. Schlueter

May 1994

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Wiggler and Undulator Insertion Devices

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May 1994

CHAPTER 14

WIGGLER AND UNDULATOR INSERTION DEVICES

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Chapter 14

WIGGLER AND UNDULATOR INSERTION DEVICES[†]

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14.1 Introduction

The acceleration of a charged particle due to a magnetic field results in photon emission perpendicular to the direction of acceleration. In the case of electrons or positrons with energy γmc^2 traveling at nearly the speed of light in a curved path (thereby accelerated), the spontaneous emission falls within a narrow cone of angular width γ^{-1} centered about the direction of electron travel and is known as synchrotron radiation (Fig. 14.1). The power of the emitted radiation is proportional to the square of the electron energy and to the square of the magnetic field.

14.1.1 Motivation for the Development of Insertion Devices

Synchrotron radiation (SR) was originally considered an undesirable by-product of storage-ring particle colliders which was produced in the bend sections of the storage ring and absorbed in the vacuum chamber wall. When the potential uses of such radiation was realized, sections of the vacuum chamber and ring shielding of these first-generation sources were modified to permit some of the radiation to leave the ring and travel through beamlines to user end stations. Second-generation storage rings were dedicated exclusively to SR generation, primarily from bending magnets. These sources targeted user-specific photon energy ranges and characteristics.

Second-generation synchrotrons led to a large increase in the use of SR for research and, as the users became more sophisticated, the demand for greater intensities and tailored characteristics for the radiation increased dramatically. This demand drove the technological development of special magnetic devices that could greatly enhance the spectral properties of the radiation. These devices consist of arrays of magnets of alternating polarity that repetitively bend electron beams back and forth as shown in Fig. 14.2. The two classes of the special magnet arrays, undulators and wigglers, are collectively known as insertion devices (IDs) because they are placed in the straight sections of storage rings. Today's third-generation synchrotrons are designed with several straight sections to maximize the use of such devices and with lower electron beam emittance to enhance the photon beam brightness, particularly from undulators. Presently, several rings, featuring very small electron beam emittance and multiple

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Fig. 14.1 An electron beam traveling in a curved path at nearly the speed of light emits photons into a narrow cone of natural emission angle $\simeq \gamma^{-1}$.

Fig. 14.2 Electrons wiggle or undulate in the midplane along the spatially periodic sinusoidal field in an insertion device.

straight sections for IDs, produce radiation in the soft x-ray regime using electron energies of 1-2 GeV. A few larger machines with electron energies of 6-8 GeV produce hard x-ray radiation. Chapter 1 includes a worldwide survey of SR ring parameters.

An ID magnet array is situated close to the electron beam so as to generate the highest possible field, yet not reduce beam lifetime by compromising the aperture for the circulating electron beam. IDs producing linear polarized radiation are usually designed to have vertical on-axis fields. Beam emittance, closed orbit errors, and injection requirements generally result in an aperture requirement that is smaller in the vertical direction, allowing attainment of smaller magnetic gaps.

The periodic magnetic field of the Fig. 14.2 insertion device is in the + or - vertical direction in the horizontal midplane. The unperturbed electron trajectory is along the longitudinal axis. The Lorentz force on the electron is at right angles to both the direction of electron motion and the magnetic field, causing the electrons to wiggle or undulate in the horizontal midplane. The period and geometrical features are chosen such that along with electron energy and wiggle field strengths, the ID yields desired radiation properties (e.g., wavelength and intensity).

14.1.2 Applications of Insertion Devices

The uses of synchrotron radiation^{1,2} are numerous and varied: (a) In the UV/soft x-ray range (10^{-7} m– 10^{-9} m), it can be used to explore the electronic structure of solids. (b) In the harder x-ray part of the spectrum ($\leq 10^{-10}$ m) it provides an excellent tool for x-ray crystallography studies to determine the three-dimensional molecular structure of proteins, which can help the pharmaceutical industry develop custom-designed drugs. (c) When absorbed by an atom, SR can cause electrons to detach or other photons to be emitted, thereby giving valuable data about the properties of the sample. (d) Circular polarized SR is extremely useful for imaging magnetic materials, which will allow the computer industry to develop advanced materials for increased data storage. (e) The coherence properties of SR can be exploited in holography to image objects with better resolution than is possible with

Fig. 14.3 Radiation beam envelope from (a) bending magnet, (b) wiggler, (c) undulator.

visible light. (f) Short SR light bursts allow stop-action spectroscopy of rapid chemical reactions. Chemical reactions can be followed precisely by tuning a free electron laser (FEL) to wavelengths easily absorbed by specific molecules. (g) Extremely short intense pulses from an FEL could make it possible to explore the dynamics of charge carriers in semiconductors.

Specific applications may require very high photon flux, wavelength selectability, spatial resolution, polarization state, time structure, or other radiation characteristics, which can be provided in machines with requisite electron beam properties coupled with specially tailored IDs.

14.1.3 Insertion Device Radiation Overview

Wigglers. Wigglers cause electron deflections that are large compared with the natural emission angle of SR, resulting in broadband emission of a fan-shaped beam of photons. Wiggler SR is similar to that produced by an individual bend magnet, but $2N$ times as intense due to repetitive electron bending over the length of a $2N$ -pole wiggler. The source depth of a wiggler is its length, typically several meters, whereas that of a bend magnet is just a few centimeters of the electrons' curved path.

Wavelength Shifters. A wavelength shifter is a wiggler with just a few poles producing high on-axis fields whose purpose is to shift the radiation spectrum toward smaller wavelengths, e.g., hard x rays, rather than to increase radiation intensity via multiple bends.

Undulators. Undulators cause small electron deflections, comparable in magnitude to the natural emission angle of the SR. The radiation emitted by an individual electron at the various poles in the magnet array interferes coherently, resulting in emission of a pencil-shaped beam of photons peaked in narrow energy bands at the harmonics of the fundamental energy. Due to the constructive interference, the radiation beam's opening angle at any given wavelength is decreased by $\sqrt{N}$ and thus radiation intensity per solid angle goes as N^2 , (assuming that the angular divergence of the electron beam is less than the natural emission angle). Fig. 14.3 contrasts the radiation beam envelope produced by a bend magnet, a wiggler, and an undulator.

Fig. 14.4 Radiation from relativistic electrons in a periodic electromagnetic field.

Coherent Synchrotron Radiation and Free Electron Lasers. For either the wiggler or the undulator, the SR from individual electrons in the beam add incoherently, and the total radiation power is the sum of the single-particle radiation power from all the electrons in the beam (i.e., total power $\propto n_e$). If instead the electrons at a given pole are all in phase, radiation amplitudes (rather than powers) from the various electrons are additive and the radiation power becomes proportional to the square of the number of electrons, n_e^2 . Such coherence, if achieved without the benefit of photon-electron interaction, is known as coherent synchrotron radiation and is bunch-length limited in present SR rings. In a free electron laser (FEL), coupling between the photon and electron beams results in a density modulation of the electron bunch, forming thin pancakes separated by one wavelength of light. The radiation from all electrons in the pancake have the same phase, and radiation amplitudes from different pancakes also add in phase. This coherence of the radiation (i.e., the linear superposition of amplitudes) produces a large gain in radiated power at the FEL frequency.

FELs can be configured as either oscillators or amplifiers. In the oscillator design, the wiggler field is inside an optical cavity. The electron beam traverses the wiggler. Emitted radiation is confined within the cavity and is reflected back through the wiggler between mirrors, thus modulating the electron beam. Coherent radiation builds up and is transmitted through a partially transparent mirror, becoming the usable laser beam. In the amplifier configuration, an electron beam passes through a wiggler coaxial with input laser light of the desired wavelength. The interaction of the laser's electric field and the electron wiggler motion causes the electrons to bunch in pancakes. The emitted photons are in phase with each other, with the radiation emitted from electrons in other bunches, and with the input laser signal. Radiation coherence and intensity increase as the electron beam makes a single pass through the amplifier. Alternatively, radiation can build up from noise in the amplifier configuration without the help of a seed laser, producing self-amplified spontaneous emission (SASE) radiation. FELs can also operate in storage rings, taking advantage of the low emittance electron beam to produce short-wavelength coherent radiation. Figure 14.4 summarizes radiation scenarios from relativistic electrons propagated through IDs.

14.2 Synchrotron Radiation From Wigglers and Undulators

Electron Equation of Motion. Integrating the equation of motion of a relativistic electron moving with average velocity $\langle v_z \rangle$ perpendicular to a sinusoidal on-axis wiggler field of magnitude $B_y = B_0 \cos k_w z$ and period $\lambda_w \equiv 2\pi/k_w$ gives, for the velocity and trajectory in the direction mutually perpendicular to $\langle v_z \rangle$ and $\vec{B}$:

$$\frac{d\vec{p}}{dt} = d\gamma m \vec{v} = e(\vec{E} + \vec{v} \times \vec{B}) \implies \frac{v_x}{c} = \frac{K}{\gamma} \sin k_w z \text{ and } x = \frac{K}{\gamma k_w} \cos k_w z, \quad (14.1)$$

where $\gamma = 1957 E[\text{GeV}]$ and deflection parameter $K \equiv e B_0 / k_w m c = .934 B_0[\text{T}] \lambda_w[\text{cm}]$.

Peak angular electron deflection and trajectory amplitude are K/γ and $K/\gamma k_w$, respectively. K , therefore, is the ratio between the radiation fan angle and the characteristic radiation cone aperture, $1/\gamma$. Thus $K \gg 1$ for wigglers, and a radiated location downstream sees emitted photons only twice per wiggler period when the sweeping electron velocity points in its direction. For undulators $K \leq 1$ and an observer downstream sees photons emitted continuously along the undulator length. The analysis can be generalized to include periodic, non-sinusoidal electron trajectories; essential radiation features remain unchanged.

14.2.1 Wiggler Radiation

The angular distribution of radiation emitted by electrons following a circular trajectory in a horizontal plane, as in a bending magnet, is³

$$\frac{d^2 F(\omega)}{d\theta d\psi} = \frac{3\alpha\gamma^2}{4\pi^2} \frac{I}{e} \frac{\Delta\omega}{\omega} \left(\frac{\omega}{\omega_c}\right)^2 (1 + \gamma^2\psi^2)^2 \left[K_{2/3}^2(\xi) + \frac{\gamma^2\psi^2}{1 + \gamma^2\psi^2} K_{1/3}^2(\xi) \right] \quad (14.2)$$

where ω is the photon frequency; θ and ψ are the observation angles in the horizontal and vertical directions, respectively; α is the fine-structure constant; I is the beam current; e is the electron charge; the subscripted K 's are modified Bessel functions of the second kind; and the argument $\xi \equiv (\omega/2\omega_c)(1 + \gamma^2\psi^2)^{3/2}$.

The two terms in the last bracket correspond to the horizontally and vertically polarized radiation. In the midplane, the second term vanishes and the polarization is purely linear. Off the midplane both terms contribute and polarization is elliptical.

The energy spectrum is smooth and broadband: peaking near, then falling off exponentially above the critical energy given by $\epsilon_c \equiv \hbar\omega_c = 3\hbar c\gamma^3/2\rho$. Half the total power is radiated above and half below the critical energy, which in practical units is

$$\epsilon_c[\text{KeV}] = 0.665 B[\text{T}] E^2[\text{GeV}], \quad \lambda_c[\text{\AA}] = 18.64 / B[\text{T}] E^2[\text{GeV}]. \quad (14.3)$$

In a wiggler, radiation from the various periods interfere incoherently. The spectrum as seen by an on-axis observer, at frequencies of interest $\omega \sim O(\omega_c)$, is for all practical purposes that of $2N$ bending magnets. The harmonic peaks are spaced so closely that they blur together.

Often several experimental end stations share the radiation fan of horizontal angular extent $2K/\gamma$. At nonzero horizontal observation angle θ , the electron's effective radius of curvature at the trajectory locations contributing to the observed radiation decreases and the off-axis critical energy becomes $\epsilon_c(\theta) = \epsilon_c(0)\sqrt{1 - (\theta\gamma/K)^2}$.

Off the midplane, circularly polarized components from successive bends cancel and the radiation remains partially linearly polarized and partially unpolarized.

14.2.2 Undulator Radiation

In an undulator, radiation from the various periods interfere coherently. Sharp peaks are produced at harmonics of the resonant frequency, which depends on the electron energy, the undulation period and field strength, and the observation position. The optical wavelength is a Lorentz transformation of the undulation period into the beam frame followed by a relativistic Doppler shift back into the laboratory frame. The velocity used in the Lorentz transformation and the Doppler shift is the longitudinal electron velocity, which is less than the full electron velocity because of the electron's curved path through the undulator. The wavelength of the fundamental radiation peak is

$$\lambda_1(\theta, \psi) = \frac{\lambda_w}{2\gamma^2} \left[1 + \frac{K^2}{2} + \gamma^2(\theta^2 + \psi^2) \right]. \quad (14.4)$$

On axis, the fundamental energy and wavelength in practical units become

$$\epsilon_1[\text{KeV}] = \frac{0.950 E_e^2[\text{GeV}]}{(1 + K^2/2)\lambda_w[\text{cm}]}, \quad \lambda_1[\text{\AA}] = \frac{13.06 \lambda_w[\text{cm}](1 + K^2/2)}{E^2[\text{GeV}]}. \quad (14.5)$$

Relative bandwidth at the n th harmonic is $\Delta\lambda/\lambda = \Delta\omega/\omega \simeq 1/nN$. As K increases, the peak spacing at the energies of interest merge and the insertion device passes from the undulator to the wiggler regime. Additionally, the resonant frequency dependence on observation angle blurs the radiation peaks for any angle-integrated sampling, resulting in a peaked spectrum superposed on top of a broadband continuum. Again, as K increases, the peaks become buried in the continuum.

The angular distribution of the radiation intensity of the n th harmonic on-axis is

$$\left. \frac{d^2 F_n}{d\theta d\psi} \right|_0 = \frac{I}{e} \frac{\Delta\omega}{\omega} \frac{\alpha N^2 \gamma^2 K^2 n^2}{(1 + K^2/2)^2} \left\{ J_{\frac{n-1}{2}} \left[\frac{nK^2}{4(1 + K^2/2)} \right] - J_{\frac{n+1}{2}} \left[\frac{nK^2}{4(1 + K^2/2)} \right] \right\}^2, \quad (14.6)$$

where the J 's are Bessel functions and n is odd. Integrated over the central cone, the flux in practical units [photons/s/0.1% bandwidth] is approximately

$$F_n = 1.451 \cdot 10^{14} \frac{NI[\text{A}] K^2 n}{1 + K^2/2} \left\{ J_{\frac{n-1}{2}} \left[\frac{nK^2}{4(1 + K^2/2)} \right] - J_{\frac{n+1}{2}} \left[\frac{nK^2}{4(1 + K^2/2)} \right] \right\}^2. \quad (14.7)$$

Brightness is a characterization of the effective radiative source size, and is given in units of flux per phase space volume:

$$B_n(0, 0) = F_n / 4\pi^2 \sigma_{Tx} \sigma_{Ty} \sigma_{Tx'} \sigma_{Ty'} \quad (14.8)$$

Fig. 14.5 (a) Typical radiation spectra from a bend magnet, a wiggler, and an undulator; and (b) spectral brightness from IDs in various facilities.

where $\sigma_{Tu}^2 \equiv \sigma_u^2 + \sigma_r^2$, $\sigma_{Tu'}^2 \equiv \sigma_{u'}^2 + \sigma_{r'}^2$, and σ_u and $\sigma_{u'}$ are the beam size and divergence in the u -direction, u being either x or y . The σ_r and $\sigma_{r'}$ are extended-source size and divergence limits for single-electron radiation. Thus, small emittance is essential to achieving a high brightness undulator radiation source. Temporally, the radiation maintains phase over a distance $l_c = \lambda(\lambda/\Delta\lambda) \simeq nN\lambda$, the coherence length.

The theory and characteristics of synchrotron radiation have been developed in detail from first principles and are reviewed elsewhere.^{4,5} Figure 14.5 shows typical on-axis photon spectra from a bend magnet, a wiggler, and an undulator along with spectral brightness from IDs in various facilities.

14.2.3 Free Electron Lasers

The interaction between electron beams and light beams underlies the physical mechanism that causes electrons to bunch into pancakes, resulting in coherent emission of radiation from the various electrons. Light amplified in the FEL propagates in the same direction as the beam, and is polarized such that its electric field lies in the horizontal plane as does the wobble motion of the electrons. The electric field of the light interacts with the electrons, causing those electrons lagging in phase with the light to gain energy and those leading in phase to slow down, resulting in a spontaneous electron bunching in thin pancake-shaped packets separated by an optical wavelength and a concurrent shift of the electric field's phase. If, in a frame moving with average electron velocity $\langle v_z \rangle$, $\vec{v} \cdot \vec{E} > 0$, then energy is transferred from the electron beam to the optical beam, and electron motion is retarded, i.e., $d\gamma/dt < 0$. The FEL resonance condition for which this coupling occurs is

$$\frac{v_z}{c} = \frac{\omega/c}{k + k_w} \simeq 1 - \frac{\lambda}{\lambda_w} \implies \gamma^2|_{res} = \frac{\lambda_w}{2\lambda} \left[1 + \frac{K^2}{2} + \left(\frac{\gamma v_{\perp, \epsilon}}{c} \right)^2 \right], \quad (14.9)$$

where ω and k are the electric field frequency and wavenumber, respectively; and $v_{\perp, \epsilon}$ is an individual electron's incremental transverse velocity due to emittance. Energy spread, emittance, and wiggle field errors must be small for the bulk of the electrons to be resonant. Thus, high brightness beams and high accuracy IDs are required for FELs.

An electron's axial velocity determines the phase relationship between its wiggle motion and the light's electric field. As electrons radiate photons they lose energy, and if B_0 is constant along the device, their average axial speed decreases and the resonant frequency for bunching changes. Axially tapering the magnetic field, so as to keep electron bunches moving at a constant average axial velocity, makes the electric field that electrons see invariant, and resonance at the original frequency is maintained along the entire device.

The lasing medium in FELs is the electron bunch in vacuum and there are no power-density limitations associated with going to high power. In contrast, conventional lasers utilize atomic transitions and, as power density increases, the heated medium interacts with the laser light, distorting the phase fronts and destroying beam quality. Thus, FELs can achieve higher power than conventional lasers at greater efficiency and are tunable over a range of wavelengths, providing unprecedented power and flexibility.

14.3 Pure Permanent Magnet Insertion Devices

The wiggle field in pure permanent magnet (PM) IDs is generated by the direct flux emanating from the PM material, some of which crosses the device's midplane. These novel devices enabled light generation in new regimes upon their introduction⁶ in the early 1980's because they are capable of higher fields than electromagnet (EM) counterparts as device dimensions (e.g., period, gap, and pole height) shrink.

14.3.1 Advantages

In addition to superior performance for short-period devices, pure PM devices are compact and require no peripheral equipment such as power supplies or cooling systems. Operating energy costs are not incurred other than the negligible amount associated with varying the gap to adjust peak on-axis field. Near unity permeability of the PM material makes these IDs immersible in other fields (e.g., a focusing quadrupole), with linear superpositioning of fields. This same characteristic, $dB/dH|_{PM} \simeq 1$, also facilitates analytical calculation of the ID field magnitude and distribution.

14.3.2 Design Methodology

Presently, the PM material of choice for IDs is neodymium-iron-boron (NdFeB), which features a remanent field $B_r \simeq 1.0 - 1.3$ T, and a coercive force $H_c \simeq$

Fig. 14.6 Permanent magnet IDs: (a) PM ID showing block magnetization directions, (b) KEK's pure PM, 179-pole, 4-cm-period undulator is situated "in-vacuum" so as to achieve 0.82 T operating at its small 1 cm magnetic gap (reprinted with permission⁷).

0.95–1.25 T, with differential permeability $dB/dH|_{PM} \simeq 1.03$ –1.05. An alternative material samarium-cobalt (SmCo), with a strength 10% less than NdFeB, features superior field-strength temperature stability (0.03% per °C versus 0.11% per °C) and superior radiation resistance.

A PM block with $H_c = 1$ T is equivalent to current sheets of strength ± 8 kA-per-cm block length, separated by the block width. As ID dimensions shrink, heat could not be dissipated in analogous high-current-density EM devices.

An ideal PM ID would consist of two rows of PM material, separated by the gap, with the easy-axis direction of the material continuously varying along the axis, rotating once per wiggle period length. In practice a pure PM ID is sectioned into several homogeneous blocks per period, as shown in Fig. 14.6. The field strength in the gap region of a two-dimensional pure PM ID of period λ_w and half-gap h , with M blocks per period, having vertical dimension L and axial dimension $\epsilon\lambda_w/M$ is⁸

$$B_z - iB_y = i2B_r \sum_{\mu=0} \cos(nk_w[z + iy]) e^{-nk_w h} \frac{\sin(n\epsilon\pi/M)}{n\pi/M} (1 - e^{-nk_w L}) \quad (14.10)$$

where harmonic $n \equiv 1 + \mu M$. The last term in parentheses quantifies the diminishing return of increasing block height L . Using a smaller number of homogeneously magnetized blocks introduces field harmonics. Still, with respect to attainable field strength, using just four blocks per period gives a peak on-axis B_0 over 90% of that for infinite segmentation. Finally, note that since on-axis ID fields arise directly from flux emanating from the PM blocks, field errors are sensitive to imperfections in PM material (e.g., dipole strength variations and easy-axis orientation errors) and to block mispositioning. A range of field strengths is usually attained by varying the gap, where peak on-axis field B_0 is proportional to $e^{-2\pi h/\lambda_w}$.

Fig. 14.7 Hybrid IDs: (a) Assembly of the lower half of the 30-pole, 12.85-cm-period, 1.4 T Beam Line X hybrid wiggler for SSRL¹⁰ (1987), (b) An early hybrid device is the 55-pole, 7-cm-period LBL/EXXON/SSRL Beamline VI wiggler¹¹ at SSRL (1982).

14.3.3 Design Variations

Alternatively, fixed-gap adjustable-phase IDs vary peak on-axis field strength by sliding one row of magnets axially along a rail.⁹ The sinusoidal variation of peak strength as the longitudinal phase between upper and lower magnet rows is shifted from 0 to $\lambda_w/2$ enables precise control of field magnitude. Electron beam vertical focusing, and thus electron beam tune, are phase-independent. Likewise, the integrated field along the beam axis, and thus beam steering, do not change with phase adjustment. The on-axis longitudinal field component in these devices gives rise to small higher order terms that alter the radiation spectra slightly from their adjustable gap counterparts.

14.4 Hybrid (Permanent Magnet Plus Iron) Insertion Devices

Hybrid insertion devices (Fig. 14.7) utilize PM material to generate flux, which by geometrical design enters directly into high-permeability, soft-iron pole pieces. An energized pole then assumes a magnetic scalar potential with respect to the midplane of the device. This potential difference drives an indirect flux out of the pole, some of which crosses the midplane, creating the desired wiggler field. The magnitude of the pole-tip scalar potential, and thus that of the on-axis field is such that direct fields into the pole from the PM material are balanced by indirect fields out of the pole arising from the potential gradient (Fig. 14.8). This equality is a physical requirement following directly from $\vec{\nabla} \cdot \vec{B} = 0$.

14.4.1 Advantages

Hybrid designs, like their pure PM counterparts, outperform EM devices as spa-

Fig. 14.8 Upper-half, quarter-period section of a typical hybrid insertion device showing net magnetic flux.

Fig. 14.9 Attainable on-axis field in pure PM and hybrid insertion devices ($B_r = 1.1\text{ T}$, $H_{pm} = -0.8H_c$).

tial dimensions shrink, and do not require electrical energy and associated cooling paraphernalia to produce field.

Additionally, for devices with small gap-to-period ratios g/λ_w , hybrid IDs outperform pure PM designs because of their ability to channel flux through the high-permeability pole pieces to the pole tip and then across the small gap. A comparison of attainable on-axis field versus gap-to-period ratio for pure PM and hybrid devices is reproduced in Fig. 14.9, assuming $B_r = 1.1\text{ T}$ and hybrid PM material operates at $-0.8H_c$ (above which point increased PM volume results in only marginally higher on-axis field).¹² For the hybrid design, attainable peak on-axis field is characterized empirically by $B_{0_{max}}[\text{T}] = 3.44e^{-g/\lambda[5.08-1.54g/\lambda]}$ over the range $0.07 \leq g/\lambda \leq 0.70$.

In hybrid devices, the field shape and quality in the region of interest is governed by the shape of the soft iron pole tip rather than the PM positioning and quality. Deviations in strengths and easy-axis orientation errors of PM blocks, problematical with pure PM devices, are more readily accommodated in hybrid designs where the PM blocks ideally do not contribute directly to the field in the gap region. Low on-axis field errors are attainable by sectioning the PM material in contact with a given pole and sorting PM blocks so that (1) average strength entering all poles is highly uniform and (2) easy-axis orientation errors of the PM material near the gap region are minimized. More subtly, the effect of perturbing sources producing direct error fields is largely negated by indirect fields arising from the presence of the iron itself.

14.4.2 Design Methodology

A quarter-period of a typical hybrid design is given in Fig. 14.8. The period is chosen such that along with electron energy and wiggler field strengths, the ID yields desired radiation properties. Again, a range of field strengths is usually attained by varying the gap.

Given ID period λ_w , a high-permeability soft-iron pole tip surface is shaped so as to obtain the desired field distribution. Subsequently, the pole scalar potential necessary to obtain the desired field strength is determined. Finally the remainder of the iron and PM is designed so as to produce this pole potential.

High-field hybrid IDs tend to saturate magnetically at the pole tip (near the gap). Analytical designs using closed-form expressions, assuming infinite permeability in the soft-iron poles, accurately predict on-axis field to the extent that the pole tip does not begin to saturate.¹³ Incorporation of results from a single 2-D magnetostatic code run in the analytical formulation can account for pole-tip saturation, while still allowing for perturbations in the design parameter space. Full three-dimensional IDs can be designed analytically to within an accuracy of $\simeq 1-2\%$. Of course any 3-D design can be modeled using a 3-D magnetostatics code. However, analytical 3-D modeling is accurate, efficient, and provides greater insight as to the effect of perturbations in the design parameter space, thereby aiding design optimization.

Low-carbon iron or vanadium permendur are the materials of choice for pole pieces. These high-permeability materials have saturation fields $B_s \simeq 2.1$ T and 2.3 T, respectively. The vanadium permendur with higher B_s , though more expensive and size-limited in availability, is magnetically preferable. Saturation for these materials effectively limits on-axis fields in hybrid IDs to $B_0 \simeq 2.0$ T–2.2 T; beyond this only marginal increments of on-axis field are attainable at an exorbitant premium in PM volume and cost, and control over the field distribution is also sacrificed.

14.4.3 Design Variations

For most ID designs, it is desirable to attain as high an on-axis field as possible, given the period λ_w , pole-tip shape, etc. Several features can be incorporated in a hybrid ID design to increase the magnetic scalar potential of the pole tip V_0 , and thereby on-axis field B_0 , within the given parameter envelope.

Permanent Magnet Overhanging and Packing. One approach to increase V_0 is to increase the direct flux Φ_d into the pole. Indirect flux Φ_i out of the pole likewise increases, and if pole size is kept invariant, the pole-pole and pole-midplane magnetic capacitances c_1 and c_0 remain unchanged. Since $\Phi_i = V_0 \Sigma_j c_j$, then V_0 , and thus B_0 increase. Overhanging PM material above the top of the pole and in the 3rd dimension beyond the lateral pole edges (as shown in Fig. 14.8) has the desired effect.¹³ Fig. 14.10(a) illustrates maximum packing of poles with PMs on top and on the sides to increase B_0 by increasing direct flux. The 2 T, 27-cm-period SPEAR Beamline 9 wiggler at SSRL employs this technique.

Weged Poles. Another method of increasing V_0 is to decrease the pole-pole capacitance. This can be accomplished by tapering the pole as shown in Fig. 14.10(b),

Fig 14.10 Hybrid insertion device field strength enhancement techniques:
(a) pole packing with PM material, (b) pole tapering.

while keeping the pole tip shape and thus the on-axis field distribution unchanged.¹⁴ Untapered, flux density in the pole decreases as one moves away from the gap. Away from the gap the pole thickness can be decreased, but not so much as to cause magnetic saturation and choke off the flux being channeled down the pole to the tip. Since direct flux Φ_d from the PM is unchanged from that in the untapered version, indirect flux Φ_i out of the pole also is unchanged, but as pole-pole capacitance decreases, pole scalar potential V_0 and on-axis flux density B_0 increase. The 0.7 T, 3.3-cm-period APS Undulator A devices at Argonne employ this technique.

14.5 Warm Electromagnet Insertion Devices

The first IDs were electromagnets arranged in an alternating array of $+/-$ dipoles. These devices generate magnetic field via $\vec{H} \cdot d\vec{s}$ around a loop enclosing the energizing current, in contrast to permanent magnet designs which generate a given amount of flux at block faces.

14.5.1 Advantages

For general SR sources, any large-period ($\lambda_w \geq 20$ cm) ID has ample real estate to house EM coils with sufficiently low current density to make energy operating costs reasonable. Capital costs for such an EM ID are significantly lower than those of a PM or hybrid counterpart. A range of field strengths is attainable by simply varying the coil current, rendering unnecessary gap changes and associated support and drive systems. Furthermore, adjustment and fine tuning of end section energization is straightforward in electromagnet IDs. Wavelength shifters, being few-pole, long-period devices, are typically electromagnets.

Fig. 14.11 Electromagnet IDs: (a) Magnetic flux lines in the upper-half quarter-period of an EM ID, (b) assembly of the lower half of the 7-full-strength plus two-half-strength pole, 45-cm-period, 2.8-cm-gap, 2-m-long, 1.9 T SSRL wiggler.¹⁵

If an FEL is to convert a significant fraction of the electrons' energy to light in a single pass, the ID's magnetic field must be tapered axially to maintain resonance (see section 2.3 of this chapter). An EM device can feature a variable, readily-tunable taper along the axis.

14.5.2 Design Methodology

In principle, EM ID design procedure parallels that of hybrid devices: (1) the pole tip surface produces the desired field distribution, (2) the pole tip scalar potential produces the desired on-axis field strength, and (3) the remainder of the coil and pole design provides the required pole tip scalar potential.

Poles of EM ID designs are connected via a high-permeability yoke to shunt the flux to the zero scalar potential plane midway between adjacent poles. (Refer to Fig. 14.11.) Assuming low $\vec{H} \cdot d\vec{s}$ losses in the iron, Ampere's law gives $\mu_0 I_{coils} = \int_{0abcdo} \vec{H} \cdot d\vec{s} \simeq \langle B_{gap} \rangle h_3$, and coil location along the pole is immaterial as far as the on-axis field B_0 is concerned. However, when coils are situated further from the pole tip, flux between adjacent poles increases and poles could saturate at the base (near the yoke), invalidating the low-pole-losses assumption. In EM designs coil current density J_c is usually set as high as heat transfer/cooling allows (typically 1000 A/cm²), thereby minimizing required coil cross-sectional area and pole height. For a given coil current, and thus on-axis field, pole flux is likewise minimized, delaying saturation of the pole base. Required pole height D_3 is given approximately by $D_3 h_2 J_c \mu_0 = \langle B_{gap} \rangle h_3$, assuming negligible pole saturation.

In an FEL, adjustment of on-axis field at any axial location along the ID should

pole number:	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18
series coil winding circuits	$\left\{ \begin{array}{cccc} \boxed{1-3-3-1} & \boxed{1-3-3-1} & \boxed{1-3-3-1} & \boxed{1-3-3-1} \\ & \boxed{1-3-3-1} & \boxed{1-3-3-1} & \boxed{1-3-3-1} & \boxed{1-3-3-1} \end{array} \right.$																	

Table 14.1 Steering-free, overlapping, 2nd-order binomial expansion coil winding pattern.

be steering-free so as not to cause displacement of the electron beam from the axis of the laser. Winding coils in series around several adjacent poles with turns ratios in a binomial expansion pattern (e.g., +1, -2, +1 or +1, -3, +3, -1), and overlapping patterns, enables steering-free local field tapering (see Table 14.1).¹⁶

14.5.3 Design Variations

Maximum attainable on-axis field in electromagnet IDs is limited by magnetic saturation in the iron pole at the base and/or by current density/heat-transfer limitations in coils. Several design techniques delay the onset of saturation until a higher pole tip scalar potential V_0 is reached.

Pole Tapering. Widening poles towards the base allows more flux to be carried where the base attaches to the common yoke, and thus delays saturation onset. Of course real estate for the coil must be sacrificed and flux between adjacent poles increases, though minimally, since the driving pole scalar potential also tapers to zero at the pole base. The tradeoff can be advantageous in certain operating regimes.

PM Reverse Biasing. PM material laced between coils or placed on lateral pole sides as in Fig. 14.12 results in a direct flux input into the pole.^{17,18} This flux does not find its way across the gap, but rather short circuits through the pole to the yoke and back through adjacent poles, thereby providing a reverse-bias flux in the pole which opposes the EM-induced pole flux. As a result, current in the EM coils, and therefore V_0 , and thus B_{0max} , can be increased before the pole begins to saturate. Of course the minimum on-axis field possible B_{0min} also increases in magnitude, and in fact at a much quicker rate than B_{0max} because laced PM displaces the coil away from the gap. Tunability range thereby decreases. Generally, reversed-biased EM IDs cannot be turned off because, in the absence of coil current, the pole saturates in the reverse direction and part of the PM induced pole flux is redirected across the gap.

Tunability Enhancement. Tunability range can be re-expanded by independently controlling the various coils around a given pole.¹⁹ B_0 depends on coil current, while the field in the iron pole B_{pole} depends on both the coil's current and its vertical location along the pole. To exploit these different functional dependencies: (1) B_0 can be maximized by locating ampturns as close to the gap as possible thereby minimizing EM-induced B_{pole} and increasing the total coil current at which the onset of saturation occurs, and (2) B_0 can be minimized by locating ampturns as far from the gap as possible thereby maximizing EM-induced B_{pole} and decreasing the total coil current

Fig. 14.12 Electromagnet ID with laced and side reverse-bias PMs enables attainment of higher B_0 (reprinted with permission¹⁹).

Fig. 14.13 On-axis magnetic flux density B_0 versus coil current I , showing EM wiggler tuning ranges (reprinted with permission¹⁹).

at which the onset of reverse-direction saturation occurs (Fig. 14.13). Figure 14.12 depicts a reversed-biased, PM-laced, tunability-enhanced EM wiggler used in an FEL for electron-cyclotron heating of a Tokamak plasma at Lawrence Livermore National Laboratory (LLNL).

Pulsed Devices. Pulsed, air-core EM devices offer the possibility of high fields for pulsed radiation applications. The ELF wiggler at LLNL employs air-core solenoids to generate a pulsed, 10-ms-period, 0.5-T on-axis field in a 10-cm-period device.²⁰

14.6 Superconducting Electromagnet Insertion Devices

14.6.1 Advantages

Long-period, few-pole superconducting wigglers (e.g., Fig. 14.14(a)) are capable of producing ultra-high fields of ~ 5 T and are ideal devices for wavelength shifters (see section 1.3 of this chapter).

At the other extreme, microundulators with $\lambda_w \leq 2$ cm offer the possibility of ultra-compact FELs for laboratory, industrial, and medical uses. Dramatically reduced-cost systems are feasible by coupling low-emittance, low-energy electron beams and high-field, short-period undulators. The entire infrared spectral range could be covered using a short-period (< 1 cm) superconducting microundulator capable of deflection values of $K \simeq 1$, with accelerator energies and undulator lengths as low as ~ 15 MeV and ~ 1 m, respectively. These superconducting DC devices are capable of the high repetition rates necessary for superconducting-linac and high-voltage electrostatic

Fig. 14.14 Superconducting IDs: (a) NSLS's 5-full-strength plus 2-half-strength pole, 17.42-cm-period, 3.2-cm-gap, 1.4-m-long, 6 T superconducting wiggler²¹, (b) BNL's continuously wound superconducting microundulator (reprinted with permission²²).

accelerator based FELs. The superconducting coils operate in relatively benign, low field environments. An inherent drawback of these devices is lack of accessibility. Alignment and magnetic characterization are difficult because the undulator is housed in a cryostat.

14.6.2 Design

A 60-cm-long superconducting microundulator with $\lambda_w = 8.8$ mm, $g = 4.4$ mm, and current density $J_c \simeq 1400$ A/mm² capable of a deflection parameter $K = 0.4$ has been tested in a visible-region FEL oscillator experiment at Brookhaven National Laboratory (BNL).^{22,23} This elegantly simple design features a continuously wound multifilament superconductor on a slotted soft iron bar that simultaneously serves as the poles, yoke, and coil mandrel (Fig. 14.14(b)). In Russia, an 8.0-mm-period device with $g = 2.5$ mm has achieved $K = 0.57$ using the same concept, while tapering the poles to delay pole saturation (see section 5.3 of this chapter).²⁴ Materials of choice for windings are Nb₃Sn tape superconductor or NbTi multifilament wire in a copper matrix.

14.7 Circularly Polarized Radiation From Insertion Devices

The amount of circularly polarized light absorbed by materials that exhibit dichroism, such as DNA and amino acids, depends on the handedness of the radiation; their presence can thus be identified, and molecular structures determined. Magnetic materials, with their inherent directional spin, also exhibit dichroism—allowing the study of magnetic characteristics of microscopic regions with important applications to magnetic storage capacity for computers.

Off-midplane bending-magnet radiation has a circular polarization component and

Fig. 14.15 A bifilar helical undulator produces circularly polarized light.

Fig. 14.16 Two planar IDs rotated 90° produce arbitrary elliptical or arbitrarily oriented linear polarization (reprinted with permission²⁷).

is often used in dichroism experiments, though high polarization degree comes by sacrificing the intensity considerably. IDs that can produce circularly polarized light (often with enhanced characteristics such as high flux intensity and/or degree of polarization at certain wavelengths) include: (a) helical devices (bifilar solenoids, planar helical undulators, and elliptical wigglers), (b) asymmetric devices, which have positive and negative poles of unequal magnitude, and (c) interference devices, in which radiation from several devices is mixed.

14.7.1 Helical Insertion Devices

The electric field component of the SR of the devices discussed thus far oscillates in only one direction in a plane perpendicular to the direction in which the light is moving. When electrons traverse a helical magnetic field, the electric field rotates azimuthally, generating elliptically polarized light with a right- or left-handedness that makes it an ideal tool to investigate materials exhibiting dichroism.

Bifilar Solenoidal Undulators. Two identical coaxial solenoids separated by half the coil-pitch λ_w , carrying current in opposite directions give rise to a circularly polarized transverse field with no longitudinal field component (Fig. 14.15). The on-axis transverse field magnitude is $B_0[\text{T}] = 8\pi 10^{-7}(I[\text{A}]/\lambda_w[\text{m}])[\epsilon K_0(\epsilon) + K_1(\epsilon)]$, where $\epsilon = \pi g/\lambda_w$ and K_0 and K_1 are modified Bessel functions. A very early FEL experiment at Stanford employing a superconducting bifilar solenoid design of 3.2-cm-period and 1.1-cm-gap with a current density of 700 A/mm² achieved a peak on-axis field of 1.3 T.²⁵ Analogous devices employing pure PM or PM plus iron, and consisting of an array of adjacent dipole magnets incrementally rotated azimuthally by an angle $2\pi/M$, are also possible.^{8,26} These devices produce relatively weak fields.

Elliptical Undulator/Wiggler. An elliptically polarized SR source consisting of two

superposed planar undulators oriented 90° about the beam axis with respect to one another produces crossed magnetic fields (Fig. 14.16).²⁷ The undulators phase-shifted longitudinally one-quarter period produce arbitrary elliptical polarization by independently varying vertical and horizontal gaps. Likewise, in-phase the undulators can produce linear polarization along an arbitrary x - y plane. Handedness could be switched slowly by mechanically varying the relative phase shift between undulators through zero, or rapidly if one of the undulators were an AC electromagnet. Horizontal field strength is limited by the vacuum chamber, which bounds the minimum horizontal magnetic gap dimension. A prototype of this design using PMs with $\lambda_w = 8.0$ cm, $g = 5.7$ cm and $B_0 = 0.15$ T in the helical mode and $B_0 = 0.21$ T in the linear mode was installed in Japan's 600 MeV Teras storage ring producing $\lambda = 63$ nm circular and linear polarized radiation, respectively.²⁸

Analogous longer-period higher-field helical devices, i.e. elliptical wigglers,²⁹ have been built for the 6 GeV TRISTAN accumulator ring and the 2.5 GeV Photon Factory at KEK.³⁰ A strong vertical field produces broadband wiggler radiation, as a relatively weak horizontal field phase shifted a quarter-period alternately bends the electron trajectory up, then down. Locally "off-axis" elliptically polarized light in the device midplane adds to that of like-handedness polarized light from subsequent half-periods also directed in the device midplane. Intense radiation with a high degree of circular polarization $P_c \simeq 0.5 - 0.9$ from the VUV to the hard x-ray regime has been produced in these devices with $\lambda_w = 16$ cm, $g = 3$ cm, and $B_0 = 1$ T ($K_y = 15$).

Pure PM Planar Helical Insertion Devices. Pure PM planar helical devices, simple to build, can generate purely circularly polarized light ($P_c = 100\%$). An advantage of these helical devices is that no part of the magnetic structure lies in the device midplane, simplifying both insertion device and vacuum chamber construction and making possible operation at smaller magnetic gap.

The European Synchrotron Radiation Facility (ESRF) pioneered the development of a planar device with (a) a split-lower jaw consisting of two PM arrays with blocks whose magnetization directions rotate longitudinally in the x - z plane, producing a vertical field component in the vertical midplane, and (b) a split-upper jaw consisting of two PM arrays with blocks whose magnetization directions rotate longitudinally in the y - z plane and differ in polarity by a half-period, producing a purely horizontal field in the vertical midplane, phase-shifted 90° (Fig. 14.17).³¹ Generation of a circular helix necessitates vertically adjusting upper and lower jaws independently so that maximum horizontal and vertical field strengths are equal "on-axis" in the desired horizontal midplane. The upper jaw assembly could be moved longitudinally over a period with respect to the lower jaw to vary helicity and/or change handedness.

Sincrotrone Trieste proposed a planar device capable of higher fields consisting of two adjacent magnet arrays each in split-upper and split-lower jaws whose blocks have magnetization directions that rotate longitudinally, alternately in the x - z and y - z planes (Fig. 14.18).³² Each jaw assembly individually produces maximum horizontal and vertical fields equal in strength at any y location in the vertical midplane,

Fig. 14.17 ESRF's planar device yields elliptically polarized light, yet does not impinge on the vacuum chamber.

Fig. 14.18 Trieste's proposed planar device produces gap-independent, circularly polarized light (handedness is invariant).

obviating independent control of jaw assemblies. Magnetization direction in PMs differs by 180° in otherwise identical upper and lower jaw assemblies, yielding maximum on-axis field strengths, variable via gap adjustment. Helicity remains perfectly circular, independent of gap, and handedness is invariant in this device.

At the Japan Atomic Energy Research Institute (JAERI), planar devices capable of even higher fields have been built³³ and proposed.³⁴ Their proposed APPLE-II planar device consists of two adjacent Fig. 14.6-type magnet arrays each in split-upper and split-lower jaws (Fig. 14.19).³⁴ Lower-front and upper-back arrays are fixed in space with block magnetization directions in the orientation of the Fig. 14.6 design. Lower-back and upper-front arrays have blocks with this same magnetization direction pattern, but shifted together longitudinally a fraction of a period to maintain a circular helix. If the longitudinal shift is fixed, varying the gap changes ellipticity somewhat. Ellipticity and handedness can be changed by longitudinally shifting together diagonal arrays.

SSRL recently commissioned a planar undulator source of circularly polarized soft x-rays in the 500-1000 eV range.³⁵ This elliptically polarizing undulator (EPU) is capable of producing linearly polarized soft x-rays in the vertical or horizontal planes, and right- and left- circularly polarized x-rays. Additionally, the four rows of NdFeB magnets are independently positionable, enabling changes in photon wavelength at a single gap. Magnet block orientations are as shown in Fig. 14.19. Axial movement of magnet rows have not measurably interfered with SPEAR electron beam parameters or other SSRL users.

Single vs. Chicane Configuration for Planar Helical IDs. Dichroism experiments usually require that the handedness of radiation can be changed. Fast cycling of the polarization's handedness can be accomplished using chicane configurations, in which the radiation from two nearly colinear devices of opposite handedness is mechanically chopped downstream of the ID, alternately giving right- and then left-circularly polarized light. Chicane configurations sacrifice monochromatic flux because radiation from only half the total periods is used at any one time; the peak width is inversely proportional to the number of periods.

Fig. 14.19 Block orientations for JAERI's proposed APPLE-II planar device and SSRL's elliptically polarizing undulator.

Fig. 14.20 Asymmetric hybrid structure generates broadband elliptically polarized light (reprinted with permission³⁷).

Relaxed handedness cycling on a time scale of the order of several seconds or minutes can be accomplished through longitudinal shifting of selected magnet arrays. This technique has the additional disadvantages of (1) possibly affecting the users on other beamlines due to slight changes in electron beam dynamics and (2) having to contend with massive, rapidly moving parts. Advantages include producing more than twice the flux of a corresponding chicane design, and use of the center of the monochromator optics, rather than the edges as with the chopped beams of the chicane design, thereby minimizing elliptical distortion.

14.7.2 Asymmetric Insertion Devices

Asymmetric Wiggler. An asymmetric wiggler produces a large positive field over a longitudinally short distance, followed by smaller negative field extended over a longer distance, so as to have a net zero integrated field over the wiggler length (Fig. 14.20). The highly asymmetric on-axis field leads to a high degree of circular polarization at photon energies from the VUV domain through the soft x-ray regime in the Super-ACO SR ring at Orsay³⁶ and in Doris III at Hasylab.³⁷ Adjustable correctors are used to keep integrated field through the ID nulled over the range of gaps.

14.7.3 Interference Devices Producing Circularly Polarized Radiation

Crossed Undulators. Crossed undulators separated by a variable phase shifter produce any desired polarization (Fig. 14.21).^{38,39} The polarization vectors of the radiation beams from a pair of in-line planar undulators oriented at right angles azimuthally are orthogonal. On-axis, the linearly polarized radiation from the two undulators can be mixed in a monochromator to produce the desired polarization state. Modulating the electron path length between the two IDs with an EM phase shifter varies the phase delay between the two radiation beams, enabling rapid, variable-waveform selection of polarization states.⁴⁰ The polarization state is very sensitive to the electron-

Fig. 14.21 Pair of crossed undulators separated by a tunable EM phase shifter (reprinted with permission⁴⁰).

beam divergence in this device, which must be restricted to $\sigma' \leq (\gamma N)^{-1}$. Thus, use is limited to low-emittance storage rings and lower energy wavelengths. A crossed undulator of this type is operating at the BESSY storage ring in Berlin, producing circularly polarized radiation in the VUV–soft x-ray range.⁴¹

14.8 Other Novel Insertion Device Design Ideas

Harmonic Generation. One approach to reaching very short wavelengths $\leq 1 \mu\text{m}$ is FEL amplification of higher harmonics. BNL's high gain harmonic generation experiment uses two superferric undulators (see section 6.2 of this chapter) separated by a dispersive section to amplify the third harmonic of a CO_2 laser.⁴² Modulation of the electron-beam energy occurs in the first (modulating) undulator, followed by electron bunching through an achromat in the dispersion section, and finally coherent radiation from the bunched electrons in a second (radiating) undulator tuned to resonate at the third harmonic, $\lambda = 3.47 \mu\text{m}$. For the radiating undulator, the wiggle period $\lambda_w = 1.8 \text{ cm}$, length $L = 1.5 \text{ m}$, deflection parameter $K \simeq 1$, and full gap $g = 0.8 \text{ cm}$.

High Electron-Beam-Energy, Short-Wavelength FELs. Alternatively, using an available high-energy, low-emittance electron beam, laser action could be extended to wavelengths as low as 0.1 nm by SASE (see section 1.3 of this chapter) or harmonic generation from a longer wavelength seed laser. Recent developments in producing low emittance beams in RF photocathode guns and in transporting and compressing beams open the possibility of such a linac-based FEL⁴³ on SLAC's 50 GeV linac in a 60-m -long, 8-cm -period ID.

Pulsed Electromagnet Microundulators. Pulsed, air-core microundulators also offer the possibility of generating ultra-high fields for compact FEL systems, even surpassing the $\sim 1\text{--}2 \text{ T}$ fields of the small-period superferric designs. FEL gain increases as K^2 , saturating when $K_{rms} \simeq 1$. Obtaining maximum gain while decreasing wiggle period below 1 cm requires on-axis fields $B_0 > 2 \text{ T}$. Circularly polarized bifilar designs (see section 7.1 of this chapter) in the pulsed mode are capable of producing these high

Fig. 14.22 Conductor configurations producing planar fields in pulsed microundulators (reprinted with permission⁴⁴).

Fig. 14.23 Millimeter-period dipole microundulator immersed in chain of alternating-polarity background fields (reprinted with permission⁴⁶).

fields. Analogous planar field designs capable of harmonic generation which feature conductors distributed over a cylindrical surface have been proposed,⁴⁴ with on-axis fields as high as ~ 5 T and $\lambda_w = 3$ mm yielding $K \simeq 1.4$ (Fig. 14.22). However, FEL repetition rate is limited in these devices so as to avoid thermal stresses and potential conductor melting associated with heat generation in small spaces. Field stability in these pulsed devices is also problematical, requiring expensive high-stability pulsed-power supplies. Finally, the absence of field-shaping iron poles makes coil-positioning fabrication tolerances exceptionally tight.

Submillimeter-Period Undulators. Submillimeter devices⁴⁵ have an inherently low deflection parameter $K \leq 0.1$, producing on-axis radiation consisting almost exclusively of the fundamental wavelength. If coherence length (see section 2.2 of this chapter) is sufficiently long, a photon-eating monochromator could be rendered unnecessary, thereby yielding reasonably high net coherent power at beamline end stations in low-energy rings (≤ 0.1 – 1.0 GeV). A potential submillimeter-period ID design consists of upper and lower jaws of PM material in which all poles are magnetized in the same direction, immersed in an external reverse-biasing field that zeros the average field on-axis. Field strength is inherently limited to half the value of remanent field B_r .

An alternative design employs an electromagnetically excited series of grooved ferromagnetic poles producing a wiggle field superposed on a dipole background.⁴⁶ A chain of such dipole-undulators with alternating polarity background fields zeros the net steering through the ID (Fig. 14.23).

At submillimeter-period dimensions these IDs are inside of the vacuum chamber. Since the aperture requirement for the circulating beam varies along the electron beam path and is proportional to the square root of the local beta function (see Chapter 2),

Fig. 14.24 Solenoid-derived wiggler: copper-plated staggered poles deflect the B-field and simultaneously support microwaves (reprinted with permission⁴⁷).

Fig. 14.25 Coaxial hybrid iron microundulator for annular beams (reprinted with permission⁴⁸).

such short-period, small-gap devices are best located in so-called low-beta sections to minimize beam scraping.

FEL IDs with Microwave Acceleration of Electrons. Axially tapering the wiggler field in an ID maintains FEL synchronism as electron beam energy is extracted (see section 2.3 of this chapter). Alternatively, microwave acceleration of electrons traversing an untapered wiggler doubling as a waveguide can keep electron energy invariant and likewise maintain electron-photon resonance. This latter technique is not susceptible to the reduction of small signal gain or to the electron detrapping phenomena associated with large-field-tapering of the former. For this microwave application, a hybrid wiggler design (see section 4.2 of this chapter) would require greatly recessed PMs to support the microwave field, and ensuing pole tip saturation would drastically limit attainable on-axis field B_0 . Alternatively, a Stanford design employs a solenoid derived wiggler structure comprising a periodic array of staggered, copper-plated ferromagnetic pole pieces which also support microwaves at the klystron frequency (Fig. 14.24).⁴⁷ Pole-tip geometry is optimized balancing relative desires for high microwave and high magnetic-field strengths. An advantage of this design is the simplicity of solenoidal field generation giving a substantial transverse wiggler field. Drawbacks include a large periodic variation in the axial B-field component and large off-axis transverse and axial gradients, leading to focusing complexities.

Annular Wiggler Devices. The coaxial hybrid iron wiggler generates large wiggler fields by imbedding a periodic array of coaxial ferromagnetic rings in a solenoidal magnetic field.⁴⁸ The central portion of the coax is shifted relative to the outer by a half-period, giving rise to a periodic axisymmetric radial field (Fig. 14.25). This design, which requires a non-standard annular beam, can produce ~ 0.4 T wiggler

fields in millimeter-period devices. Its relatively small field gradients give superior beam focusing and transport properties. Simulations predict that a wiggler based amplifier in the K_u -band at ~ 15 GHz and 200 kV could yield high gain ($> 1\text{dB}/\lambda_w$), efficiency ($> 10\%$), and power (several megawatts).

Inverse Free-Electron Lasers. Wigglers can also be used as an inverse free electron lasers, where the energy from a high power laser beam transfers energy to a coaxial electron beam. A fast-excitation pulsed iron-core EM wiggler for this purpose has been developed at Brookhaven.^{49,50} Eddy currents induced in copper field reflectors laced between wiggler poles effectively uncouple the axially alternating polarity wiggle field, significantly enhancing the maximum achievable on-axis field. An on-axis field of $B_0 = 1.8$ T with a $200\text{-}\mu\text{m}$ pulse length has been achieved in a 3.7-cm -period, 0.4-cm -gap device. Poles consist of thin laminations which are removable so as to allow axial tapering of the wiggle period.

Multi-Undulators. Several facilities, including SSRL, HASYLAB, and the Photon Factory, have incorporated in their rings multiple interchangeable undulators mounted on a readily movable carriage. These devices allow a single beamline to use a range of different undulator periods, or polarizations in the case of the SSRL device, and hence extend the energy and polarization available to the user.

14.9 Insertion Device Fields and Errors

14.9.1 Field Requirements

Undulator Radiation Driven Field Requirements. The intensity of light in a spectral peak is limited by both electron beam characteristics (see Chapter 2) and ID field errors. An undulator should produce high brightness in several harmonics so as to span a broad energy range. Attaining the appropriate phase of the emitted light throughout the device necessitates maintaining the appropriate electron path trajectory. This in turn requires a high-quality on-axis field, establishing error tolerances on the undulator structure.

Random field errors vertically perpendicular to the beam axis cause light production over a broad range of frequencies, thereby reducing brightness in spectral peaks. Kincaid derived a relationship from a statistical ensemble average between allowable random field error σ_{rms} and reduction in peak intensity.⁵¹ Results for a 30% intensity reduction of the n th harmonic peak in an N -period device are reproduced in Fig. 14.26. The effect of magnetic field errors on emitted radiation is actually quite complicated; it is the change in trajectory length downstream of a perturbation

$$\Delta s(z) = \int \left\{ \left[1 + (x'_0 + \Delta x'_0)^2 \right]^{1/2} - \left[1 + x_0'^2 \right]^{1/2} \right\} dz \quad (14.11)$$

that affects the light. Here $x_0(z)$ is the electron trajectory in an ideal field $B(z) = B_0 \cos k_w z$, and $\Delta x_0(z)$ is the trajectory perturbation caused by a field perturbation $\Delta B(z)$. The nature of the effect on the light, (e.g., the production of harmonics, the reduction of the fundamental's peak, and broadening and shifting of spectral lines)

Fig. 14.26 Peak spectral intensity reduction, random field errors of magnitude σ : G_Δ , F_Δ characterize intensity loss and peak position shift for small, large orbit walks [$g \equiv \sigma^2 N^3$, $p \equiv n/N(1 + 2/K^2)$] (reprinted with permission⁵¹).

1st int. n dip.	$\leq 100 \text{ Gcm}$
1st int. s dip.	$\leq 100 \text{ Gcm}$
2nd int. n dip.	$\leq 10000 \text{ Gcm}^2$
2nd int. s dip.	$\leq 10000 \text{ Gcm}^2$
int. n quad.	$\leq 100 \text{ Gcm/cm}$
int. s quad.	$\leq 100 \text{ Gcm/cm}$
int. n sext.	$\leq 100 \text{ Gcm/cm}^2$
int. n oct.	$\leq 100 \text{ Gcm/cm}^3$

Table 14.2 Typical storage ring driven integrated field multipole requirements (int $\equiv$ integrated, n $\equiv$ normal, s $\equiv$ skew, dip $\equiv$ dipole, quad $\equiv$ quadrupole, etc.)

is dependent on the nature of the field perturbation (e.g., steering or steering-free, symmetry with respect to unperturbed field, and perturbation magnitude), and can be determined explicitly by evaluating the expression given above.

Systematic field errors such as axial variation of B_0 or λ_w produce a shift in radiation wavelength, thus broadening spectral peaks, whereas total power in peaks remains virtually unchanged. The characteristic linewidth for a perfect ID is determined by electron beam characteristics, the number of periods N , and harmonic number n . For a single electron, $\Delta\lambda/\lambda \simeq \Delta\omega/\omega \simeq 1/nN$. Machine dependent restrictions on variations in K and λ_w can limit broadening of the spectral peak FWHM to a specified percentage beyond that of a perfect ID with the given electron beam and accelerator operating in its normal mode (e.g., multibunch).

FEL Driven Requirements. The field kick from each pole of an ID changes the angle of the electron's trajectory with respect to the beam axis. Each individual bend must be of precisely the same size to keep the beam from receiving a net deflection. Random errors in the wiggler field can result in an undesired "random walk" of the electron beam which, in the case of an FEL, would eventually result in the separation of the electron beam and the laser light, degrading FEL performance.

Additionally, in any ID the shape of the electron beam must be preserved. Even in the absence of ID field errors, the nonzero beam emittance may require focusing in long devices.

Storage Ring Driven Field Requirements. Interestingly, the first wiggler in a storage ring was used to control the beam.⁵² Specifically, this "Robinson wiggler" redistributed damping rates to simultaneously damp synchrotron and horizontal and

vertical betatron oscillations in an alternating-gradient ring for which the horizontal betatron oscillation is normally anti-damped. Linear and nonlinear beam dynamics can be studied quantitatively through the use of SR integrals;⁵³ high field wigglers can selectively modify these integrals and are still used today to control emittance, bunch length, energy spread, and spin polarization in non-SR applications. First use of a wiggler as a light source was on the SPEAR storage ring at SSRL.⁵⁴

Ideally, IDs for SR would be decoupled from the accelerator electron optics, and thus could be inserted or removed at will. Yet, since $ev_x B_z$ always points towards the midplane in the periodic magnet array, where z is the axial direction and x is the transverse (wiggle) direction, IDs naturally provide vertical electron beam focusing. Adjustment of storage ring quadrupoles can compensate for this natural ID focusing, however this breaks the periodicity of the storage ring, thereby reducing the dynamic aperture. Additionally, spatial field harmonics in the periodic ID structure contribute to perturbing forces that limit the acceptance of the storage ring. Both effects can lead to a reduction in beam lifetime. A good lattice design will cause the ID-induced dynamic aperture reduction to be dwarfed by that produced by field errors in other realizable ring magnets (see Chapter 2).

ID error fields cause a variety of storage ring problems. Nonzero first and second field integrals through the ID missteer and displace the beam, respectively. The horizontal distortion of the electron orbit, so produced, can be amplified at other ring locations, adversely impacting the performance of other beamlines which require a highly stable photon flux. Nonzero integrated quadrupole, sextupole, and octupole integrals focus and missteer off-axis particles. Furthermore, as the field level in a given ID changes, these integrated fields could change, thereby requiring active magnet tuning control around the ring. Therefore, it is desirable to design IDs with integrated field errors small and independent of gap so as to minimize disruption of the rest of the ring during operation.

Typical specifications for integrated multipoles in third generation rings are listed in Table 14.2. Orbit stability is discussed fully in Chapter 13.

14.9.2 Insertion Device Design Implications

Insertion Device Wiggle Plane Focusing Schemes. Beam focusing in the short IDs of ≤ 5 m in storage rings is not usually an issue. Longer undulators and very low emittance beams in FELs require focusing to preserve the small size of the electron beam. Vertical structure devices naturally provide vertical focusing. Several design techniques can provide horizontal (wiggle plane) focusing. Pure PM IDs can be imbedded in a conventional external quadrupole and the superpositioning of fields is nearly linear. In hybrid devices, PM material may be positioned inside the pole tips, oriented so as to give an on-axis gradient.⁵⁵ Alternatively, poles can be canted or wedged in the transverse direction to produce x -direction focusing. Finally, focusing can be introduced by employing parabolic-shaped pole tips.⁵⁶ For FEL applications, this latter technique has the advantage of preventing modulation of the electrons' longitudinal velocity, which could result in a change of the phase of the electron with

respect to the electromagnetic wave, thereby causing electron debunching and loss of gain.

Insertion Device End Effects. The entrance and exit of an ID should be steering-free so emitted photons are directed accurately to the beamline and so the electron orbit stays on track, respectively. This can be accomplished in iron dominated IDs by energizing end poles of a uniform array using a binomial expansion of pole tip scalar potentials.¹⁶ Using an odd number of poles coupled with a second order binomial expansion end excitation pattern ($\hat{V}_i = 0, +1/2, -1, +1, -1, \dots + 1, \dots, -1, +1, -1, +1/2, 0$) has the advantage of yielding zero net electron displacement at the ID exit, in addition to being steering-free. Conversely, an even number of poles coupled with a second order binomial expansion end excitation pattern ($\hat{V}_i = 0, +1/2, -1, +1, -1, \dots + 1, -1, +1, -1/2, 0$) results in a net electron displacement $2\langle\Delta x\rangle$ at the ID exit, where $\langle\Delta x\rangle$ is the average electron displacement through the ID. However, it has the advantage of being steering-free even if the ID ends have steering errors, since their opposite polarities negate one another. Regardless of the number of poles, third order binomial expansion end excitation patterns ($\hat{V}_i = 0, +1/4, -3/4, +1 - 1, +1, \dots \pm 1, \mp 1, \pm 3/4, \mp 1/4, 0$) have the additional desirable feature of zero average electron displacement $\langle\Delta x\rangle$ throughout the ID, thus eliminating the odd poles advantage seen in the second order pattern. EM devices achieve these end pole potentials without difficulty by scaling end pole energization currents. Hybrid designs may achieve this by scaling PM material size at the last few poles⁵⁷ or by recessing tips of end poles;⁵⁸ either method attempts to approximate the designed ideal excitation over a range of gaps. Errors in placing a pole on its correct scalar potential propagate through an ID, decaying exponentially. Iron-free PM designs can be made steering-free and displacement-free independent of gap by appropriate orientation, sizing, and spacing of the PM material at device ends.⁵⁹

ID Field Errors. ID error fields arising from (1) iron pole, EM coil, and/or PM positioning/orientation errors, (2) PM strength and global/local easy-axis misorientation errors, and (3) iron pole nonuniformities, including saturation effects, collectively must cause neither excessive spectral performance degradation nor storage ring electron beam perturbations.

Any field perturbing source can be described by equivalent magnetic charges, which can be decomposed into charge distributions that are symmetric and antisymmetric with respect to the midplane, as illustrated in Fig. 14.27. Symmetric field errors $\Delta B_y(z)$ are perpendicular to the midplane in the midplane and lead to both a horizontal displacement and steering of the beam. Antisymmetric field errors are parallel to the midplane in the midplane. Those errors $\Delta B_z(z)$ that are also parallel to the electron trajectory have no detrimental effects. Those errors $\Delta B_x(z)$ parallel to the midplane, but perpendicular to the electron trajectory, cause vertical beam steering and displacement.

In pure PM or ironless EM IDs, the induced on-axis error field strengths and distributions are calculable in closed form. For systems with iron, hybrid theory¹³ enables

Fig. 14.27 Field perturbing sources can be decomposed into symmetric and antisymmetric components for field error analyses.

semi-analytical calculation of error fields. Mechanical and magnetic specifications can be made in conformance with given spectral and accelerator requirements. PM block sorting and dimensional tolerancing minimize field errors.

Additionally, contoured pole surfaces can provide local multipole field correction. After ID assembly, transverse arrays of vertically adjustable trim magnets⁶⁰ positioned at ID ends can also correct for any residual integrated multipole (i.e. normal and skew dipole and quadrupole) errors over a range of gaps.

Permanent Magnet Characteristics and Quality. A PM easy-axis orientation error at axial position z_q of a block with magnetization direction parallel to the beam axis gives rise to an even on-axis field error, $\Delta B_y(0, 0, z - z_q)$, causing both a beam displacement and (only by virtue of 3-D effects) a net steering. Such orientation errors are important only on PM block surfaces near the midplane and in principle could be corrected before assembly by grinding block surfaces; in practice one sorts blocks and positions only the best (i.e. those with low misorientation) near the gap. Typically the easy-axis of good quality PM blocks deviates from the nominal direction by less than 1%–3%.

An error in the magnetization strength of a PM block with the magnetization direction parallel to the beam axis gives rise to an odd on-axis field error, $\Delta B_y(0, 0, z - z_q)$, causing a beam displacement, but no net steering. In a hybrid design, sorting PM blocks so as to average the strength of the various blocks in contact with a given pole reduces this effect to a negligible level. Typically the strength of good quality PM blocks deviates from the nominal magnitude by less than 2%.

In a pure PM device, strength and magnetization-direction orientation errors in a block with the magnetization direction perpendicular to the beam axis give rise to even and odd on-axis field errors, respectively.

Quality PM blocks must maintain linearity well into the third quadrant of the B-H curve and must exhibit good temperature stability.

Tolerances. Both gap and pole thickness errors result in an even on-axis field error distribution. A space between PM and a pole also gives rise to a non-zero $\int_z B_y(0, 0, z) dz$. Typical tolerances on these dimensions are 50 μm –100 μm .

Iron Characteristics and Quality. Magnetic saturation of soft iron components limits attainable fields. Variations of the saturation behavior of different parts of the system's iron (e.g., due to voids, or nonuniform heat treatment or composition) can give rise to random field errors, which are difficult to predict. Additionally, saturation can give rise to a gap-dependent integrated sextupole. When the iron permeability $\mu \gg 1$, this potential error source vanishes.

14.10 Power and Power Density Considerations

Thermal load on beamline and optical components intercepting the ID's photon beam must be accommodated. Lower energy photons impinging on high-atomic-number materials deposit their energy on the materials' surface. Conversely, the energy of higher energy photons can be absorbed and scattered throughout the depth of a lower-atomic-number material such as carbon. The angular distribution of power in an ID is⁶¹

$$\frac{d^2 P}{d\theta d\psi} = P_T \frac{21\gamma^2}{16\pi K} G(K) f_K(\gamma\theta, \gamma\psi), \quad (14.12)$$

where $G(K)$ and $f_K(\gamma\theta, \gamma\psi)$ are given by

$$G(K) = K \frac{(K^6 + 24K^4/7 + 4K^2 + 16/7)}{(1 + K^2)^{7/2}} \quad \text{and} \quad (14.13)$$

$$f_K(\gamma\theta, \gamma\psi) = \frac{16K}{7\pi G(K)} \int_{-\pi}^{\pi} d\alpha \left(D^{-3} - 4D^{-5}(\gamma\theta - K \cos \alpha)^2 \right) \sin^2 \alpha, \quad (14.14)$$

and where $D = 1 + \gamma^2\psi^2 + (\gamma\theta - K \cos \alpha)^2$ and f_K is normalized so that $f_K(0,0) = 1$. P_T is the total ID power. In practical units, power and power density are, respectively,

$$P[kW] = 1.267 E^2 [\text{Gev}] \langle B^2 \rangle [\text{T}] I [\text{A}] L [\text{m}] \quad \text{and} \quad (14.15)$$

$$\frac{d^2 P}{d\theta d\psi} [\text{W} \cdot \text{mr}^{-2}] = 10.84 B_0 [\text{T}] E^4 [\text{Gev}] I [\text{A}] N G f_K. \quad (14.16)$$

14.11 References

1. *Handbook on Synchrotron Radiation*, ed. G.S.Brown and D.E.Moncton, (North-Holland, 1991).
2. *Synchrotron Radiation Research: Advances in Surface and Interface Science*, ed. R.Bachrach, (Plenum, 1992).
3. J.D.Jackson, *Classical Electrodynamics* (Wiley, 1975) 674.
4. S.Krinsky, *IEEE Trans. Nucl. Sci.* **NS-30** (1983) 3078.
5. K-J.Kim, *Nucl. Instr. Meth.* **A261** (1987) 44.
6. K.Halbach, et al., *IEEE Trans. Nucl. Sci.* **NS-28** 3 (1981) 3136.
7. S.Yamamoto, *Rev. Sci. Instr.* **63** (1992) 400.
8. K.Halbach, *Nucl. Instr. Meth.* **187** (1981) 109.
9. R.Carr, *Nucl. Instr. Meth.* **A306** (1991) 391.

10. E.Hoyer, et al., *1987 IEEE Part. Accel. Conf.* **3** (1987) 1508.
11. E.Hoyer, et al., *Nucl. Instr. Meth.* **208** (1983) 117.
12. K.Halbach, *J. Physique C1* **44-2** (Feb. 1983) C1-211.
13. K.Halbach, *Law. Berk. Lab. Rep.* V-8811-1.1-16 (1989).
14. N.A.Vinokurov, *Nucl. Instr. Meth.* **A246** (1986) 105.
15. G.Brown, et al., *Nucl. Instr. Meth.* **208** (1983) 65.
16. K.Halbach, *Nucl. Instr. Meth.* **A250** (1986) 95.
17. K.Halbach, *Nucl. Instr. Meth.* **A250** (1986) 115.
18. G.Deis, et al., *IEEE Trans. on Magetics* **24-2** (1988) 1090.
19. R.Schlueter and G.Deis, *Nucl. Instr. Meth.* **A331** (1993) 711.
20. T.J.Orzechowski, *Phys. Rev. Lett.* **57-17** (1986) 2172.
21. H.Hsieh, et al., *IEEE Trans. Nucl. Sci.* **NS-28 3** (1981) 3292.
22. K.Batchelor, et al., *Nucl. Instr. Meth.* **A296** (1990) 239.
23. I.Ben-Zvi, et al., *Nucl. Instr. Meth.* **A318** (1992) 781.
24. V.A.Papadichev, et al., *Nucl. Instr. Meth.* **A331** (1993) 748.
25. L.R.Elias and J.M.Madey, *Rev. Sci. Instr.* **50** (1979) 1335.
26. G.Bekefi and J.Ashkenazy, *Appl. Phys. Lett.* **51-9** (1987) 700.
27. H.Onuki, *Nucl. Instr. Meth.* **A246** (1986) 94.
28. H.Onuki, et al., *Appl. Phys. Lett.* **52** 173.
29. S.Yamamoto, et al., *Jap. J. Appl. Phys.* **26-10** (1987) L1613.
30. S.Yamamoto, et al., *Rev. Sci. Instr.* **60-7** (1989) 1834.
31. P.Elleaume, *Nucl. Instr. Meth.* **A291** (1990) 371.
32. B.DiViacco and R.P. Walker, *Nucl. Instr. Meth.* **A292** (1990) 517.
33. S.Sasaki, *Nucl. Instr. Meth.* **A331** (1993) 763.
34. S.Sasaki, *Proc. 8th Nat. Conf. on Synch. Rad. Instr.* Gaithersburg (1993).
35. R.Carr and S.Lidia, *SPIE 2013 E-Beam Sources of Hi-Brit. Rad.* (1994).
36. J.Goulon, et al., *Nucl. Instr. Meth.* **A254** (1987) 192.
37. J.Pfluger, *Rev. Sci. Instr.* **63** (1992) 295.
38. M.Moissev, et al., *Sov. Phys. J.* **21** (1978) 332.
39. K-J.Kim, *Nucl. Instr. Meth.* **A219** (1984) 425.
40. M.A.Green, et al., *1991 IEEE Part. Accel. Conf.* **2** (1991) 1088.
41. J.Bahrtdt, *Rev. Sci. Instr.* **63** (1992) 339.
42. X.Zhang, et al., *Nucl. Instr. Meth.* **A331** (1993) 689.
43. C.Pellegrini, et al., *Nucl. Instr. Meth.* **A341** (1994) 326.
44. R.W.Warren, *Nucl. Instr. Meth.* **A304** (1991) 765.
45. R.Tatchyn, P.Csonka, in *Und. Mags. for SR & FELs*, World Sci. (1988) 71.
46. N.V.Smolyakov, *Nucl. Instr. Meth.* **A308** (1991) 80.
47. A.H.Ho, et al., *Nucl. Instr. Meth.* **A296** (1990) 631.
48. R.H.Jackson, et al., *SPIE 2013 E-Beam Sources of Hi-Brit. Radiation* (1994).
49. A.vanSteenbergen, *US Pat.* 368618 (Aug. 1990).
50. J.Gallardo, et al., *IEEE Trans. on Mag.* **30-4** (1994).
51. B.Kincaid, *J. Opt. Soc. Am. B* **2** (1985) 1294.

52. K.W.Robinson, *Phys. Rev.* **111-2** (1958) 373.
53. M.Sands in *Proceedings of the International School of Physics "Enrico Fermi"*, Course XLVI, ed. B.Touschek, (Academic Press, 1971).
54. M.Berndt, et al., *IEEE Trans. Nucl. Sci.* **NS-26-3** (1979) 3812.
55. R.Tatchyn, *SLAC-PUB-6186* (1993).
56. E.T.Scharlemann, *J. Appl. Phys.* **58-6** (1985) 2154.
57. U5.0 Conceptual Design Report, *Lawrence Berk. Lab. PUB-5256* (1989) 30.
58. I.Vasserman and E.R.Moog, internal APS note, unpublished (1993).
59. K.Halbach, unpublished.
60. E.Hoyer, *Law. Berk. Lab. Rep. LSME-570.* (1993).
61. K.-J.Kim, *Nucl. Instr. Meth.* **A246** (1986) 67.

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